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AN ANALYTICAL SOLUTION OF LIFT LOSS
FOR A ROUND PLANFORM WITH A CENTRAL LIFTING JET

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LIST OF SYMBOLS

d	Exit diameter of the jet
D	Diameter of the planform
$\overline{D}$	Equivalent diameter of the planform
h	Height of the planform from the ground plane
HR	Height Reynolds Number ($\rho Vh/\mu$)
JR	Jet Reynolds Number ($\rho Vd/\mu$)
p	Static pressure
P	Pressure parameter ($T/8\pi h^2$)
p_i	Static pressure at the jet exit
p_{io}	Dimensionless static pressure at the jet exit (p_i/P)
q	Strength of the source flow
r	Radial distance from the jet centerline
r_o	Radius of the jet exit ($d/2$)
R_o	Dimensionless jet exit radius (d/D)
RN	Reynolds Number defined as $\rho VD/\mu$
S	Lift loss
T	Thrust of the jet
v	Radial velocity
V	Mean exit velocity of the jet
μ	Coefficient of viscosity
ν	Kinematic viscosity
ρ	Density

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ABSTRACT

An analysis of the lift loss for a round planform fitted with a centrally-located round jet is presented. The pressure distribution over the lower surface of the planform is solved analytically by matching an inner viscous solution with an outer potential solution. By comparing the calculated pressure distributions with NACA experimental data, satisfactory agreement has been obtained, although the planforms are not exactly the same. In addition, Wyatt's formula for the lift loss is found to be essentially valid, but only under limited conditions, and an improved formula is suggested. Additional works, both experimental and theoretical, needed to solve the lift loss problem are discussed with recommendations.

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INTRODUCTION

The problem of lift losses for V/STOL aircraft in hovering flight is of critical importance for its development and design, and has been reviewed by Margason (reference 1) and Walters and Henderson (reference 2). Although a variety of prediction methods for the jet induced lift losses are available ranging from essentially complete reliance on testing to complex computerized methodologies, both accuracy and reliability of these methods have been found to be deficient compared against experimental data (see, e.g., reference 2). This is due to insufficient data base in some cases, but the inadequacies of the methodologies in terms of aerodynamic modeling and analytical basis also play a significant part.

Multiple lifting jets in ground effect may produce a fountain which upon impingement on the aircraft can supply a lift increment. The net lift loss for this case is the difference between the jet-induced suckdown force and the fountain lift increment. An analysis of the fountain lift increment has been presented in reference 3. In the present work, an analytical solution for the suckdown for a round planform with a centrally-located single lifting jet is reported. A study of the multi-jet suckdown will be reported elsewhere (reference 4).

In the prediction methods developed by Kuhn (reference 5) and Karema and Ramsey (reference 6), the basic analytical tool is a formula of the lift loss for an "equivalent single jet" (i.e., a single jet with an equivalent circular planform). However, these formulas have been obtained entirely from correlating experimental data. Not only have different empirical approaches yielded different formulas for the lift loss, but "discrepancy between the results from two apparently almost identical experiments" has also been found by Wyatt (reference 7).

The present work is basically an analytical one. The pressure distribution over the planform is determined by matching a potential solution with a viscous solution. By numerical integration of the pressure distribution, the suckdown force is obtained. An analysis of the present results has substantiated to a large extent Wyatt's formula for the lift loss, but its limitations as well as needed improvements can be identified. In the present analysis, the emphasis is on the basic aerodynamic features of the problem, and only circular planforms will be considered.

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EXPERIMENTAL WORKS

An experimental study of the lift losses for single jet configurations (i.e., single jets issuing from various circular, rectangular and triangular plates) has been conducted by Wyatt (reference 7). His formula for the lift loss or suckdown force is

$$\frac{S}{T} = 0.012 \left(\frac{h}{\bar{D} - d}\right)^{-2.3} \tag{1}$$

where

h = height of the planform above the ground plane

d = jet diameter

$\bar{D}$ = angular mean diameter of the planform

T = jet thrust

For a centrally located jet in a circular planform $\bar{D} = D$. The geometrical parameters in Wyatt's experiments are as follows approximately: $0.1 \leq d/D \leq 0.3$, $0.15 \leq h/D \leq 1.2$. In addition, the values of the jet Reynolds Number $JR = Vd/\nu$, where V is a mean jet efflux velocity and ν the kinematic viscosity coefficient, are in the range from 1.0 to 3.1×10^6.

Wyatt was unable to correlate his results with those from an earlier work by Spreemann and Sherman (reference 8). He found that to apply equation (1) to NACA results in reference 8, the power index should be changed to -2.02 and the proportional constant to 0.025. In addition to the lift losses, the induced pressures on the lower surface of two square plates have been measured by Spreemann and Sherman. Their graphs show the pressure distributions dependent on the values of h/d and the plate size. An examination of the pressure distributions suggests that there are two distinct regions of different aerodynamic characteristics.

The induced pressure distributions on the lower surface of a 40-inch diameter disc with one inch jet diameter at three values of h, i.e., 5, 3 and 2 inches have also been measured by Gelb and Martin (reference 9). Their results are qualitatively similar to those obtained by Spreemann and Sherman. In addition, Gelb and Martin found that at a height of two inches, the jet filled the annular space and the flow became "a radial uniform flow". At a height of 5 inches, there was an inflow toward the jet exit over a substantial portion of the lower surface of the disc.

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ANALYSIS-MATCHED POTENTIAL AND VISCOUS SOLUTION FOR THE PRESSURE DISTRIBUTION

In figure 1, two streamline patterns for the jet-induced flow field near a circular plate are shown. Figure 1a shows a purely radial flow expected to be valid for $h/D \ll 1$ as found by Gelb and Martin for $h/D = 0.05$. The flow pattern in figure 1b, consistent with that obtained by Gelb and Martin with $h/D = 0.125$ and $d/D = 0.05$, is designated as the case $h/D < 1$. Its range of validity may extend to $h/D \sim 0.5$ depending on the jet Reynolds Number.

The pressure distributions over the lower surface of the plate are also sketched in figure 1. These distributions are in general accord with the experimental evidences. In particular, both distributions are shown to have two distinct regions with unique, but different, aerodynamic characteristics. The inner and outer regions of pressure distribution can be considered as viscous and potential pressure distributions, respectively, since their main features can be defined by the viscous and potential flow solutions to be presented in the following.

It must be added that figures 1a and 1b are not the only possible flow patterns under the condition $h < D$. As pointed out by Spreemann and Sherman in reference 8, a trapped "doughnut" shaped vortex may form under the plate depending primarily upon the size of the plate (i.e., the value of $d/\bar{D}$). For such a trapped vortex flow pattern, the pressure distribution appears to be largely of a viscous nature, and no potential pressure region is present (see figure 19b in reference 8 for a 6-inch square plate with $d/\bar{D} = 0.1667$ and $h/d = 1.0$). It is expected, however, that, subject to further study, the trapped doughnut vortex occurs at values of $h/\bar{D}$ lying between those for figures 1a and 1b, and only for limited values of $d/\bar{D}$. Consequently, the trapped vortex flow pattern will not be treated in the present study. Of course, the results presented here may be inadequate at such values of $d/\bar{D}$.

Potential Pressure Distribution

An examination of the flow shown in figure 1a suggests the use of a potential source to describe the flow in the annular space at least in the outer region. For figure 1b, it is proposed to approximate the flow close to the lower surface in the outer region by a potential sink flow. The potential pressure distribution is to be matched with a viscous distribution in the inner region, and the extent of the region of validity for the potential flow will be determined.

The velocity potential of a source or sink is

$$\phi = \frac{q}{2\pi} (\log r + C) \tag{2}$$

where q is the strength of the source (positive) or sink (negative), r the radial distance and C an arbitrary constant. The radial velocity is

$$v = \frac{d\phi}{dr} = \frac{q}{2\pi} \frac{1}{r} \tag{3}$$

The static pressure p is given by

$$p = p_o - \frac{1}{2} \rho \left(\frac{q}{2\pi}\right)^2 \frac{1}{r^2} \tag{4}$$

where p_o is a constant. By taking p = o at D/2, p_o is found to be

$$p_o = 2\rho\left(\frac{q}{2\pi}\right)^2 \frac{1}{D^2}$$

Thus, in the outer region the pressure is

$$p = -\frac{1}{2}\left(\frac{q}{2\pi}\right)^2 \left(\frac{1}{r^2} - \frac{4}{D^2}\right) \tag{5}$$

For h/D<<1 (figure 1a), the strength q can be determined from the conservation relation $\pi r_o^2 V = qh$, where $r_o = d/2$. For the case h/D<1, shown in figure 1b, the inflow is produced by the jet entrainment of the ambient fluid. In the absence of adequate information for the entrainment, a dimensional analysis has yielded the following modified conservation relation

$$\pi r_o^2 V = \lambda q h, \tag{6}$$

where λ is a dimensionless entrainment factor expected to be generally greater than one, but approach one as h becomes small. The entrainment factor should in general depend on JR and d/D as well as h/D.

It is convenient to refer the lift loss to the jet thrust $T = \pi r_o^2 \rho V^2$, and to nondimensionalize the pressures with respect to

$$P = \frac{T}{8\pi h^2} \tag{7}$$

Consequently, in the outer region the pressure is given by

$$\frac{p}{P} = -\frac{r_o^2}{\lambda^2}\left(\frac{1}{r^2} - \frac{4}{D^2}\right) \tag{8}$$

<u>Viscous Pressure Distribution</u>

It is well known that when the plate is close to the ground plane (h/D<<1), the solution of the flow can be simplified (see, e.g., reference 10). The pressure is related to the velocity potential by the following formula

$$p = -\frac{12\mu}{h^2}\,\phi \tag{9}$$

where μ is the coefficient of viscosity. Thus, using equation (2)

$$p = \frac{12\mu}{h^2}\,\frac{q}{2\pi}\log\left(\frac{r}{r_o}\right) - p_i, \tag{10}$$

where p_i is the static surface pressure at the jet exit. Spreemann and Sherman's measurements show p_i dependent on h/d, and it may also vary with the jet Reynolds Number and the ratio d/D. However, p_i is not well defined at this time, and is considered as a parameter in the present analysis. In dimensionless form, the viscous pressure in the inner region for the case h/D<<1 is

$$\frac{p}{P} = -\frac{48}{HR}\,\frac{1}{\lambda}\log\left(\frac{r}{r_o}\right) - p_{io} \tag{11}$$

where HR is the height Reynolds $\rho V h/\mu$, and $p_{io} = p_i/P$.

For the case $h/D<1$, the pressure distribution given by equation (8) is strictly speaking not applicable. However, in the inner region, especially at large values of HR, the flow has the characteristic of a dead water region and the pressure variation is small. Thus, the use of equation (8) is quite acceptable as will be seen from the numerical analysis to be given in the following section.

NUMERICAL RESULTS AND COMPARISON WITH EXPERIMENTAL DATA

From the above analysis, the following significant parameters for the lift loss of a circular flat planform with a centrally-located jet can be identified:

$\frac{d}{D}$ - Ratio of jet diameter to planform diameter

$\frac{h}{D}$ - Ratio of planform height to its diameter

p_{io} - Dimensionless surface pressure at jet exit (p_i/P)

JR - Jet Reynolds Number $(\rho Vd/\mu)$

λ - Jet entrainment factor

The height Reynolds Number HR = $\rho Vh/\mu$ evidently can be written as the product of JR, h/D, and D/d. However, in the numerical evaluation of the present solution, it is more convenient to use HR. In fact, the lift loss can be written in the following form

$$\frac{S}{T} = \frac{D^2}{h^2} \; f\left(\frac{d}{D}, \, HR, \, p_{io}\right) . \qquad (12)$$

The above formula shows the dependence of the lift loss on the height h comes from two parts, h^{-2} and HR. Thus, the power -2.3 in Wyatt's work may be only of limited validity. The following numerical analysis will prove that this is indeed the case. In addition, the power of (D-d) is found to be generally different from that of h.

Numerical evaluation of the solution has been carried out for a large number of cases with d/D and p_{io} in the following ranges:

$$0.00 < d/D < 1.00$$

$$0.00 < p_{io} < 0.20$$

The values of HR are divided into two categories: one "low height Reynolds Number", from 100 to 1000, and the other one "high height Reynolds Number, from 10^4 to 10^6. The numerical results will be presented in these two categories. However, very little experimental data for the low HR category are available, and to the V/STOL aircraft technology only the high HR case is of primary interest. Consequently, only the high HR results will be compared with the experimental data obtained by Wyatt, and by Spreemann and Sherman.

Low Height Reynolds Number (HR)

For low height Reynolds Numbers, with values ranging from 100 to 1,000 (to 4,000 in some cases), the entrainment factor λ equals to 1. In fact, jet entrainment plays no role in the suckdown or lift loss for this case.

Typical pressure distributions are shown in figures 2 and 3. Note the changes in the viscous portion of the distributions as the height Reynolds Number is increased. The potential pressure portion, however, remains the same.

The lift loss in terms of $h^2 S/16\pi D^2 T$ plotted versus $(1-d/D)^2$ for various values of HR and p_{io} is given in figures 4, 5 and 6. Some significant features of these results should be noted. First of all, the lift loss is shown to vanish at both ends of the $(1 - d/D)^2$ scale, i.e., for $d/D = 0$ and 1.0. Thus, the suckdown force generally has a peak, which for HR = 500 and $p_{io} = 0.02$ occur close to $(1-d/D)^2 = 0.5$ or $d/D = 0.293$ (figure 5). These peaks shift to higher or lower values of $(1-d/D)^2$ as p_{io} decreases or increases. On the other hand, the peak moves to a higher value of $(1-d/D)^2$ as HR increases.

In addition, the larger the value of p_{io} the larger the lift loss. In fact, lower bounds of the liftloss are obtained for $p_{io} = 0$.

Figures 4, 5 and 6 show that the lift loss depends on the height Reynolds Number. Thus, in addition to the power h^{-2}, the lift loss also varies with h through $HR = \rho Vh/\nu$ as can be seen from figure 7. It is of interest to note, however, this dependence is not in the form of a single power. At a value of $d/D = 0.05$, the dependence can be approximated by -0.2 power. At $d/D = 0.2$, the power is found to be -0.33. This is illustrated graphically in figure 8, in which the factor $HR^{.3}$ is introduced to the lift loss to determine if a power -2.3 for h is an adequate approximation. Since the three curves for HR = 500, 1,000 and 3,000 do not reduce to a single curve, clearly this approximation is not uniformly valid over the whole range $0 < d/D < 1.0$. In the region near the peak suckdown, the deviation can be as large as 10% from the mean.

High Height Reynolds Number (HR)

In Wyatt's experiments, the height Reynolds Number covers the range from HR = 5.0×10^5 to 3.72×10^7. According to Wyatt, in Spreemann and Sherman's work the jet Reynolds Number is 0.5×10^6 compared with 1.0 to 3.1×10^6 in his work. Consequently, the measurements by Wyatt, and by Spreemann and Sherman are in the high height Reynolds Number range.

To make computations using equations (6), (8) and (11), for this case it is necessary to know the value of the entrainment factor λ as a function of JR, d/D and h/D. At the present time, such information is not available, and in the present work several constant values of λ are used in the analysis.

From equations (8) and (11), it is observed that as λ is increased from one to larger values, the magnitude of both the potential and viscous pressures will reduce in magnitude. The reduction in the potential pressure will be larger, since it is proportional to λ^{-2} instead of λ^{-1} in the viscous pressure. The magnitude of the lift loss will consequently drop in a nonlinear manner when λ increases.

For illustration, figures 9 and 10 show the comparison between the pressure distributions measured by Spreemann and Sherman (figure 19(a), reference 8) and calculated by using several values of λ. The measurements were made for a 10-in square plate with $d/\bar{D} \simeq 0.10$, and results for h/d = 1.0 are shown in figure 9, while those for h/d = 0.5 in figure 10. The calculated results are for HR = 10^4 and for λ = 1.0 and 1.2 in figure 9 and λ = 2.0, 2.2 and 2.5 in figure 10. The agreement between the measurements and calculations appears to be good at least qualitatively.

Some significant points, however, should be noted. In the present analysis, the pressure is assumed to have the ambient value at the edge of the plate. This is consistent with Gelb and Martin's results. But reference 8 does not give any pressure data at the plate edge. In addition, the pressure distributions for h/d = 2.0 and 4.0 in figure 19(a) of reference 8 do not evidently have enough details to show upon inspection any definitive pattern, viscous, viscous-potential or otherwise. Whether they do or do not reach the ambient value at the plate edge is uncertain. Although these two cases of higher h/d values are of interest to the lift loss problem, no meaningful evaluation or comparison appears possible without additional, more accurate measurements. Moreover, there is no reason to expect these two distributions to be not of the viscous-potential type shown in figure 1b.

It is of interest to point out that a method of determining the entrainment factor λ is to measure the surface pressures and compare them with calculations for several well chosen values of λ. The correct λ value is that yielding the best agreement between the measurements and calculations. Although the agreement shown in figures 9 and 10 appears to be satisfactory, the results do not necessarily constitute an accurate determination of λ for the present cases.

Irrespective of the uncertainty in the entrainment factor λ, the general characteristics of the lift loss can be stated as follows:

(1) The lift loss $h^2S/16\pi D^2T$ plotted versus $(1-d/D)^2$ with HR and p_{io} as parameters vanish at both ends of the scale, i.e., for $d/D = 0$ and 1.0.

(2) The lift loss has a peak at some immediate value of d/D depending on HR and p_{io}. For example, $h^2S/16\pi D^2T$ peaks at $d/D = 0.245$ for $HR = 10^6$ and $p_{io} = 0.01$ (with $\lambda = 1.0$).

(3) In addition to h^{-2}, the lift loss S varies with h through the height Reynolds Number. This additional dependence cannot be accurately expressed as a single power for example -0.03 as shown in figure 11.

These characteristics are of the same nature as those for the low HR case.

A typical plot of the lift loss versus $(1- d/D)^2$ is given in figure 12. To use such graphs for analysis, it is necessary to know the parameters p_{io} and λ for given values of HR and d/D. This requires additional study beyond the scope of the present analysis.

To make a comparison with Wyatt's experimental results, it is convenient to present the results in the form of $Sh^{2.3}/T$ as a function of $(1-d/D)^{2.3}$. It is noted, however, in reducing the numerical data the jet Reynolds Number, the height Reynolds Number, h/D and d/D are related. To be consistent, the following procedure is used. First, the thrust of the jet is kept constant as d/D is changed. Thus Vd/D is maintained as a constant. Secondly, define a Reynolds Number $RN = \rho VD/\mu$, and take $RN = 10^7$ at $d/D = 0.02$. Then at any other d/D, the value of RN equals $(D/5d)^2 x10^7$. An example of such a data reduction is shown in figure 13 for HR = 10^5, p_{io} = 0.001, and λ = 1.0. In this figure, Wyatt's formula, equation (1), becomes a straight line, although his experimental data cover only a limited range. These two graphs intersect at the point I. Thus, based on the present results, the surface pressure at the jet exit p_{io} for $(1-d/D)^{2.3}$ = 0.615 or d/D = 0.1905 has the value of 0.001. No data for p_{io} were given in Wyatt's report.

In view of the uncertainties involving the parameters it does not appear to be meaningful to use Wyatt's formula for the determination of p_{io}. Instead, the following empirical formula is proposed

$$\left(\frac{h}{D}\right)^{2.3} \frac{S}{T} = 0.013\left(\frac{d}{D}\right)^{0.05} \left(1 - \frac{d}{D}\right)^{2.25} \tag{13}$$

Figure 13 shows the above formula to be a good approximation to Wyatt's. This formula has the characteristic that it vanishes at d/D = 0 and 1.0. Additional improvements, however, are needed to include, for example, the effects of the jet Reynolds Number.

From the above comparison, it can be stated that

(1) Wyatt's formula may have only limited range of validity in the values of d/D and JR, and it does not predict peak suckdown forces, which appear to exist based on the present analysis.

(2) The power -2.3 for h in Wyatt's formula can be considered as an acceptable approximation in limited ranges of the parameters.

(3) There is no evidence that the factor (1-d/D) should have the power of 2.3 The dimensionless quantities h/D and 1-d/D are independent of each other.

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CONCLUSIONS AND RECOMMENDATIONS

The present method of viscous and potential pressure matching appears to be capable of predicting acceptable pressure distributions over the lower surface of a round planform in a hovering mode. The agreement between the predictions and the experimental results by Spreemann and Sherman (reference 8) as shown in figures 9 and 10 is satisfactory. However, as pointed out already, the planform used in the present analysis is different from that used in Spreemann and Sherman's measurements. In addition, the value of HR used in the calculations is 10^4. It is not certain about the actual HR value in Spreemann and Sherman's experiments. The difference in HR values, if any, may compensate the difference in the planform shape. However, it is believed that the basic approach of the present method has been largely substantiated as sound.

Two quantities in the problem cannot be predicted from the present method, i.e., the entrainment factor λ and the exit pressure p_i. Both quantities should depend on the parameters JR and d/D, if not sensitively on HR. Thus, the assumption of constant values for λ and p_i in the calculations should be abandoned as soon as such information becomes available. Such information should also be used to determine the peak values of the suckdown force.

Evidently, additional experimental and theoretical works are needed to solve the lift loss problem. In the experimental area, it is recommended that

(1) Careful measurements be made for the surface pressures, including p_i, for various meaningful values of h/D, JR, HR and d/D.

(2) Measurements of the flow entrainment and a determination of the entrainment factor λ be conducted.

(3) Accurate determination of the flow patterns (figures 1a and 1b and the trapped doughnut vortex pattern, e.g.), and measurements of the lift losses.

(4) Measurements should be conducted for the single jet first and extended to multi-jet cases.

The present analysis has delineated some general characteristics of the lift loss problem for a single jet. An extension of the analysis to multi-jet cases is under consideration. The use of an advanced computational method with an efficient scheme, either in finite difference or finite element methodology, is certainly very desirable, and potentially more productive. The effects of turbulent transport processes at high height Reynolds Numbers should be studied by such a method with a suitable turbulence model. It is recommended that such a task be undertaken immediately.

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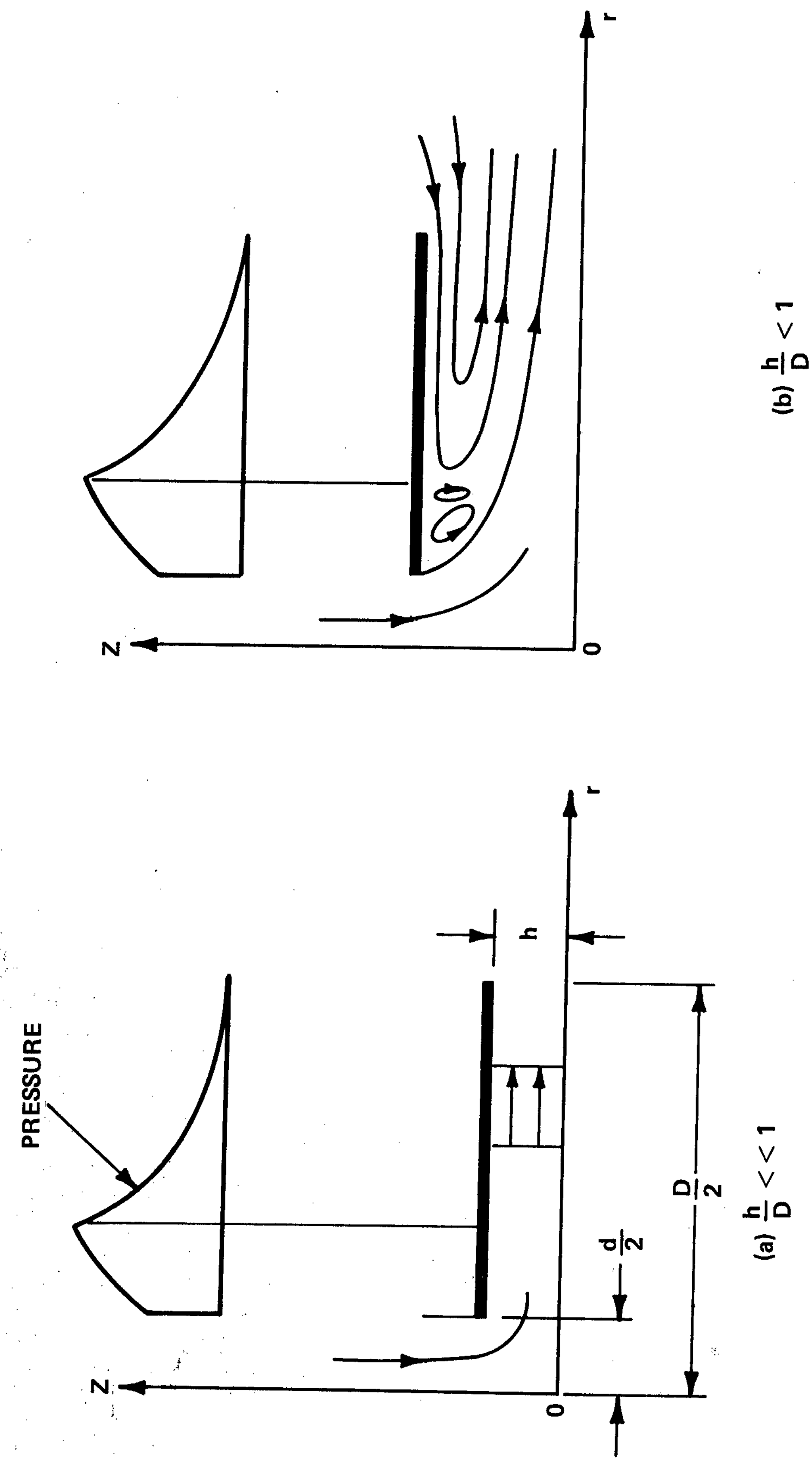

Figure 1. Flow Patterns Induced by the Jet

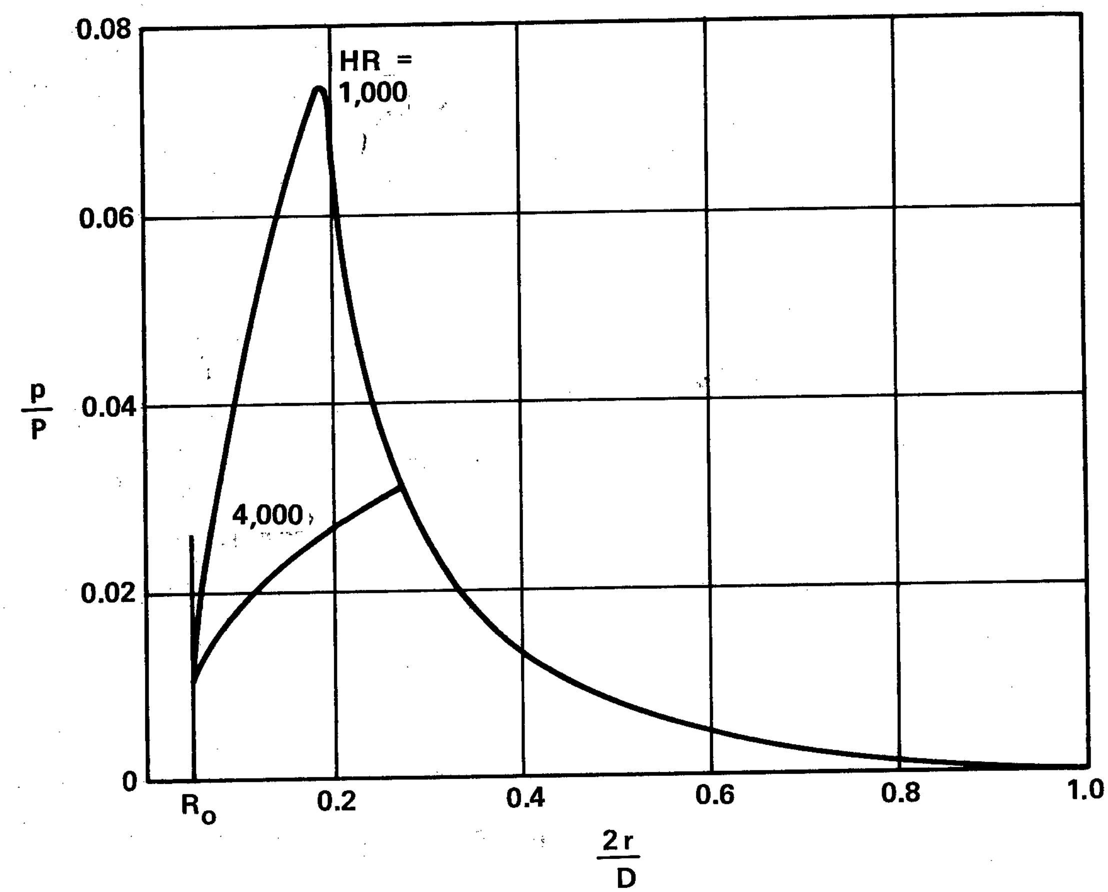

Figure 2. Surface Pressure Distributions for HR = 1,000 and 4,000, p_{io} = 0.01

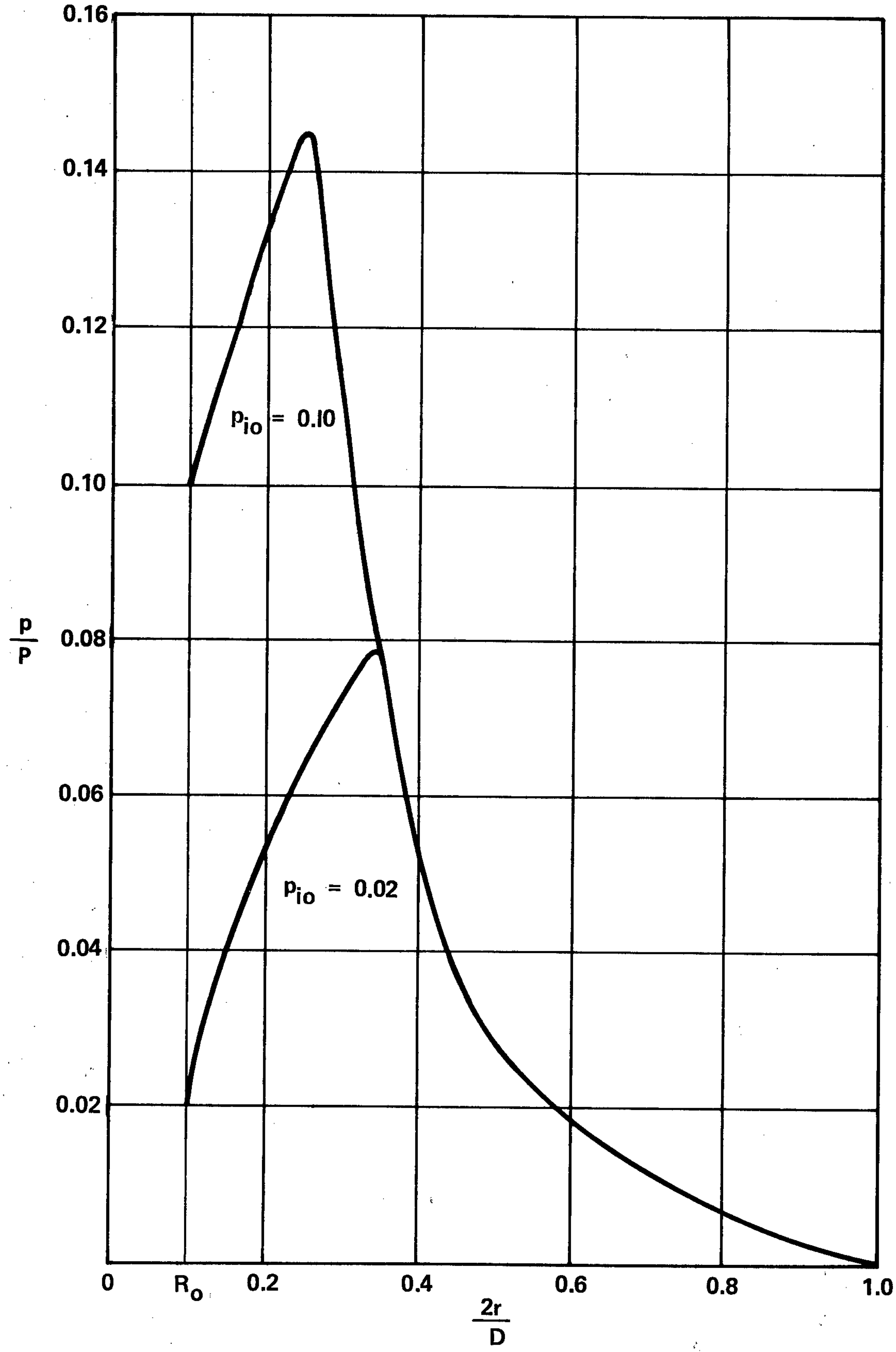

Figure 3. Surface Pressure Distributions for HR = 1,000 p_{io} = 0.02 and 0.1

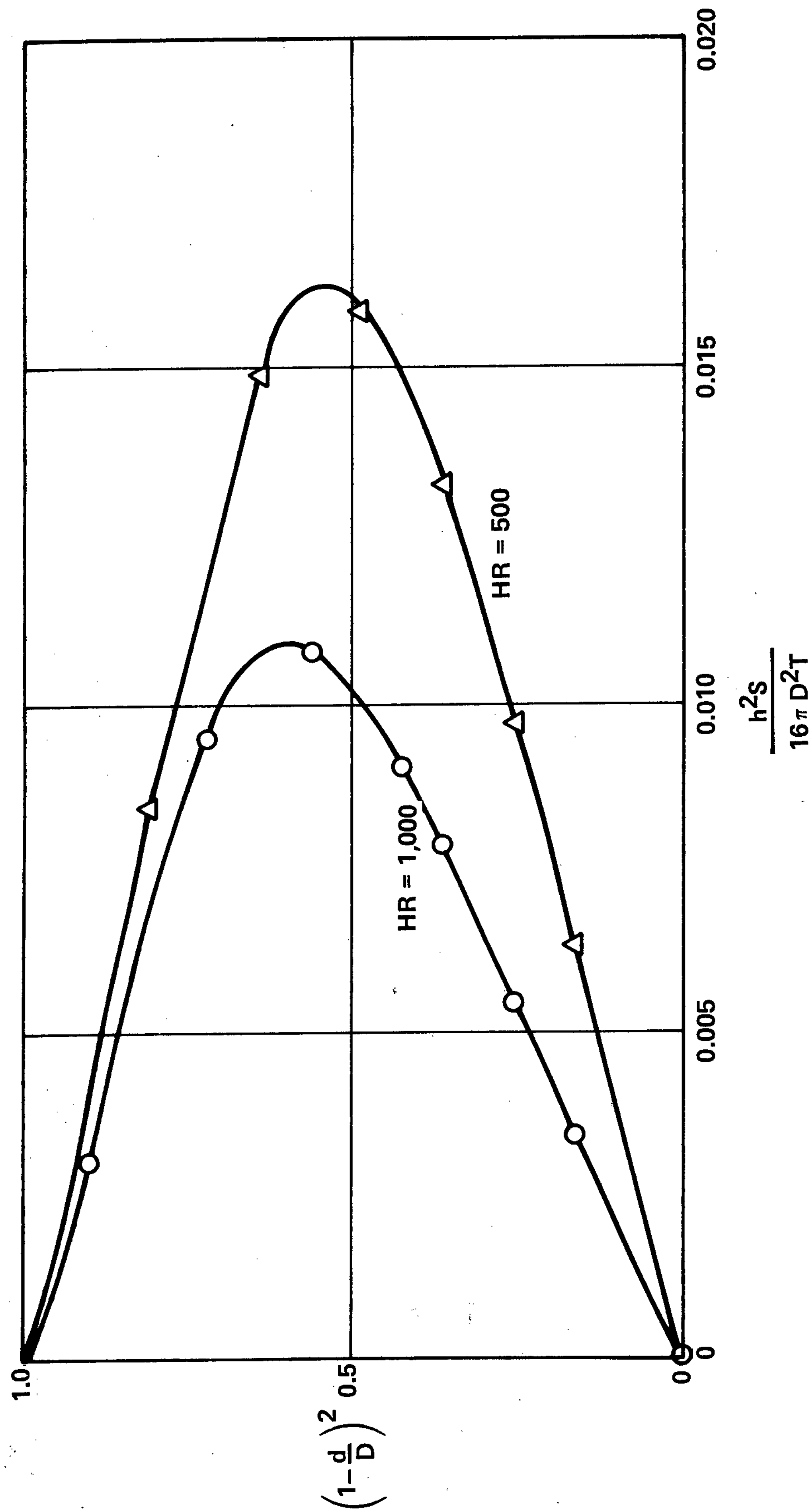

Figure 4. Lift Loss $h^2S/16\pi D^2T$ for $P_{io} = 0$

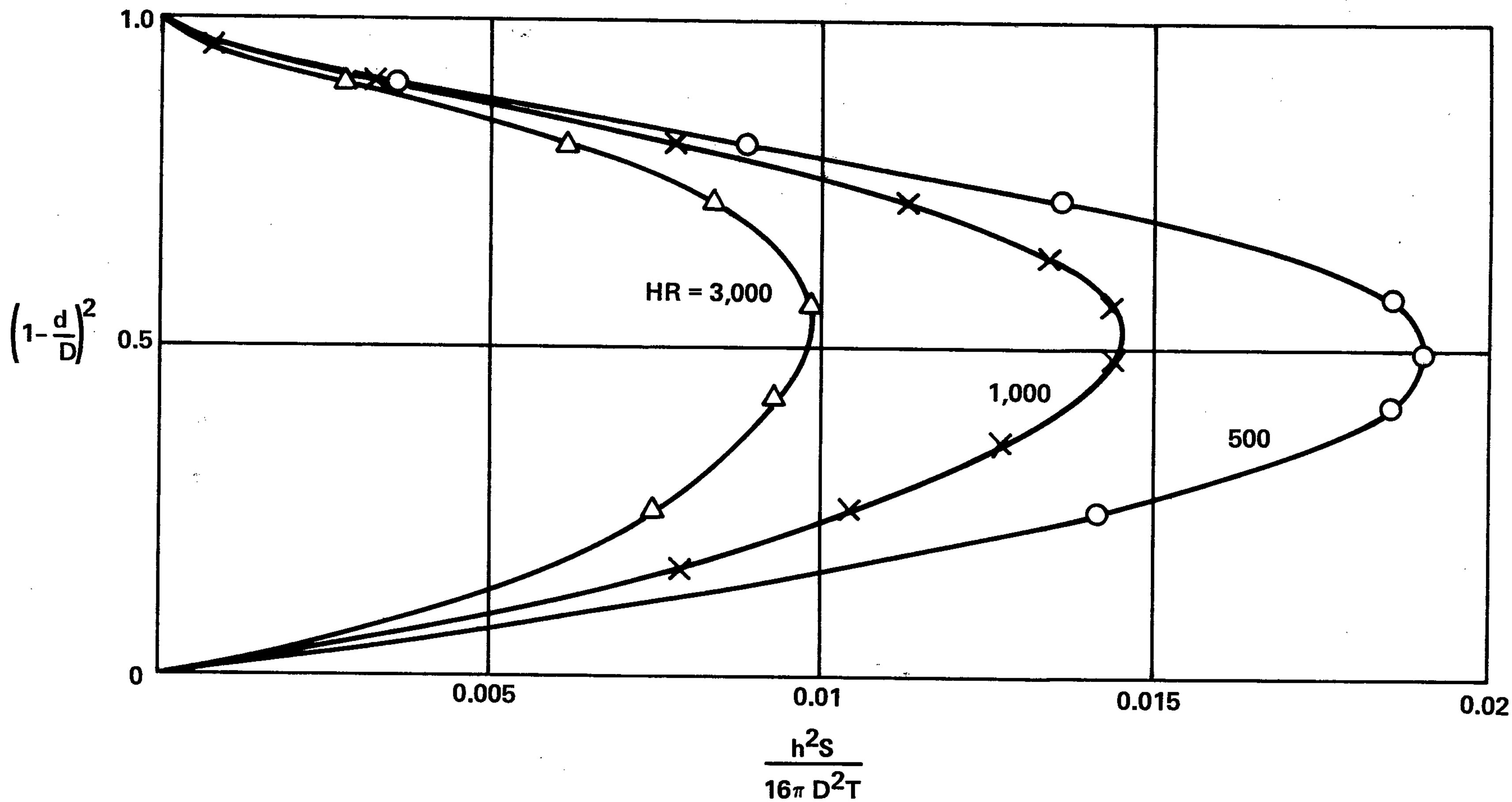

Figure 5. Lift Loss $h^2S/16\pi D^2T$ for $p_{io} = 0.02$

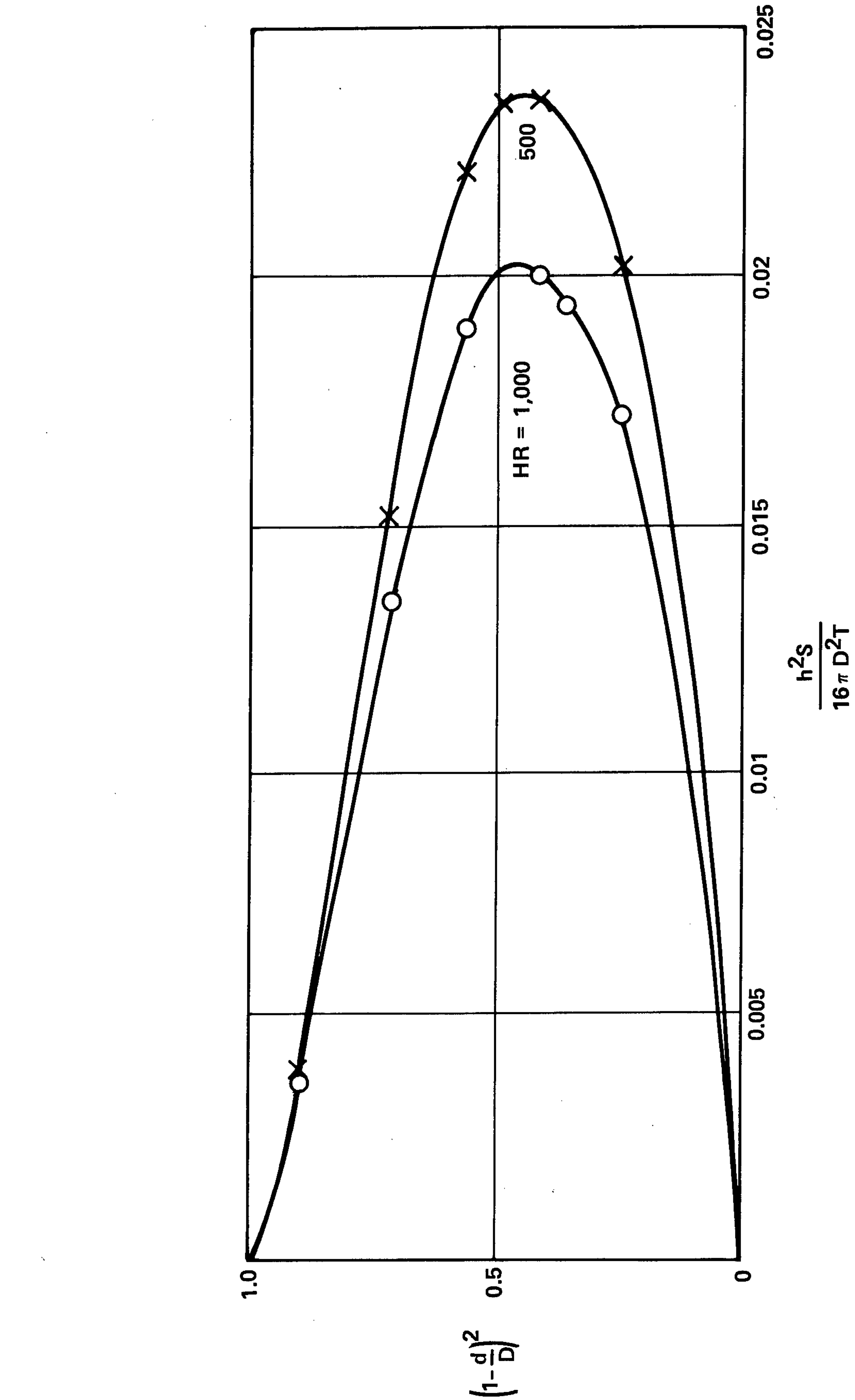

Figure 6. Lift Loss $h^2S/16\pi D^2T$ for $P_{io} = 0.05$

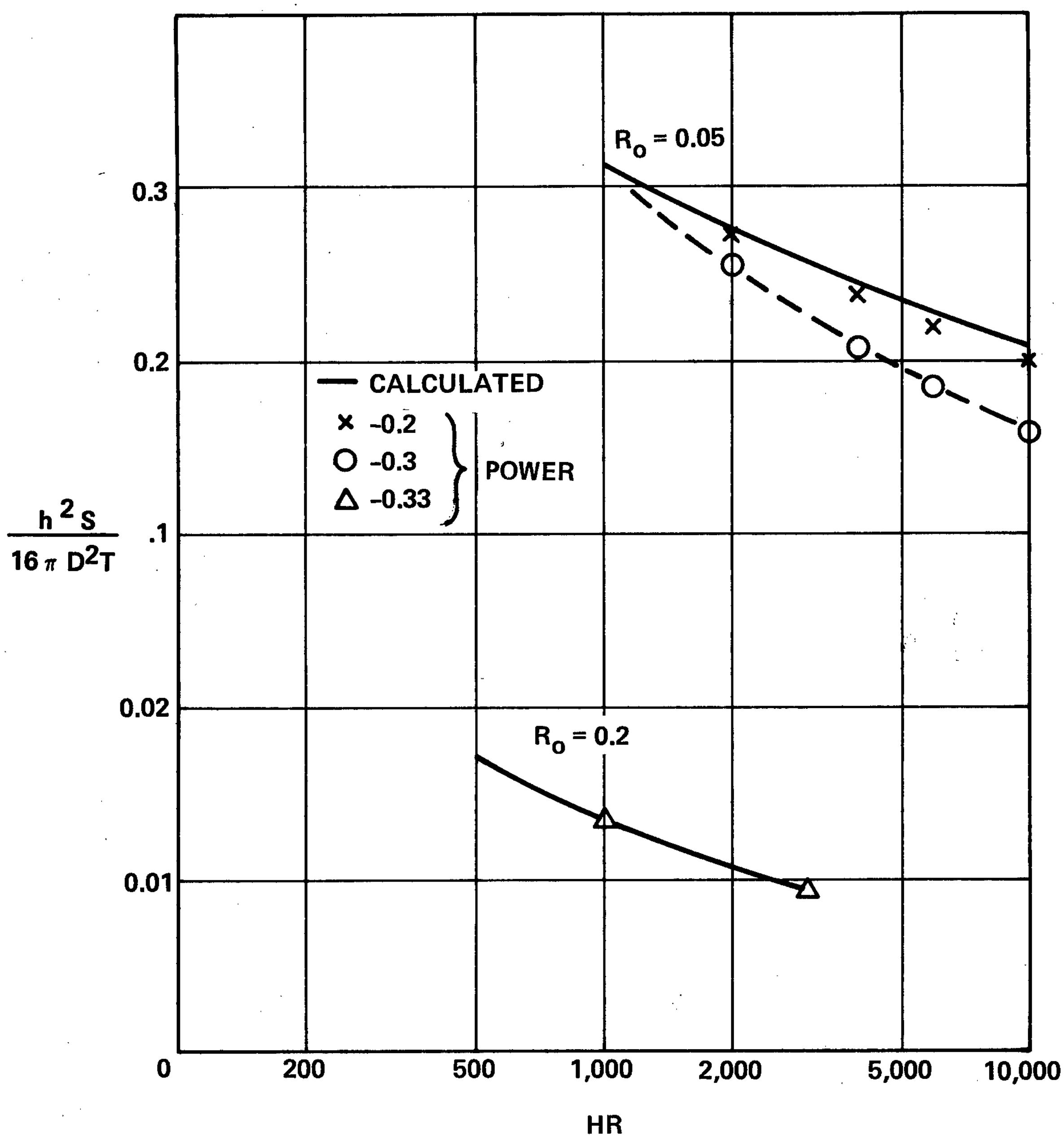

Figure 7. Dependence of $h^2S/16\pi D^2T$ on HR - Low HR

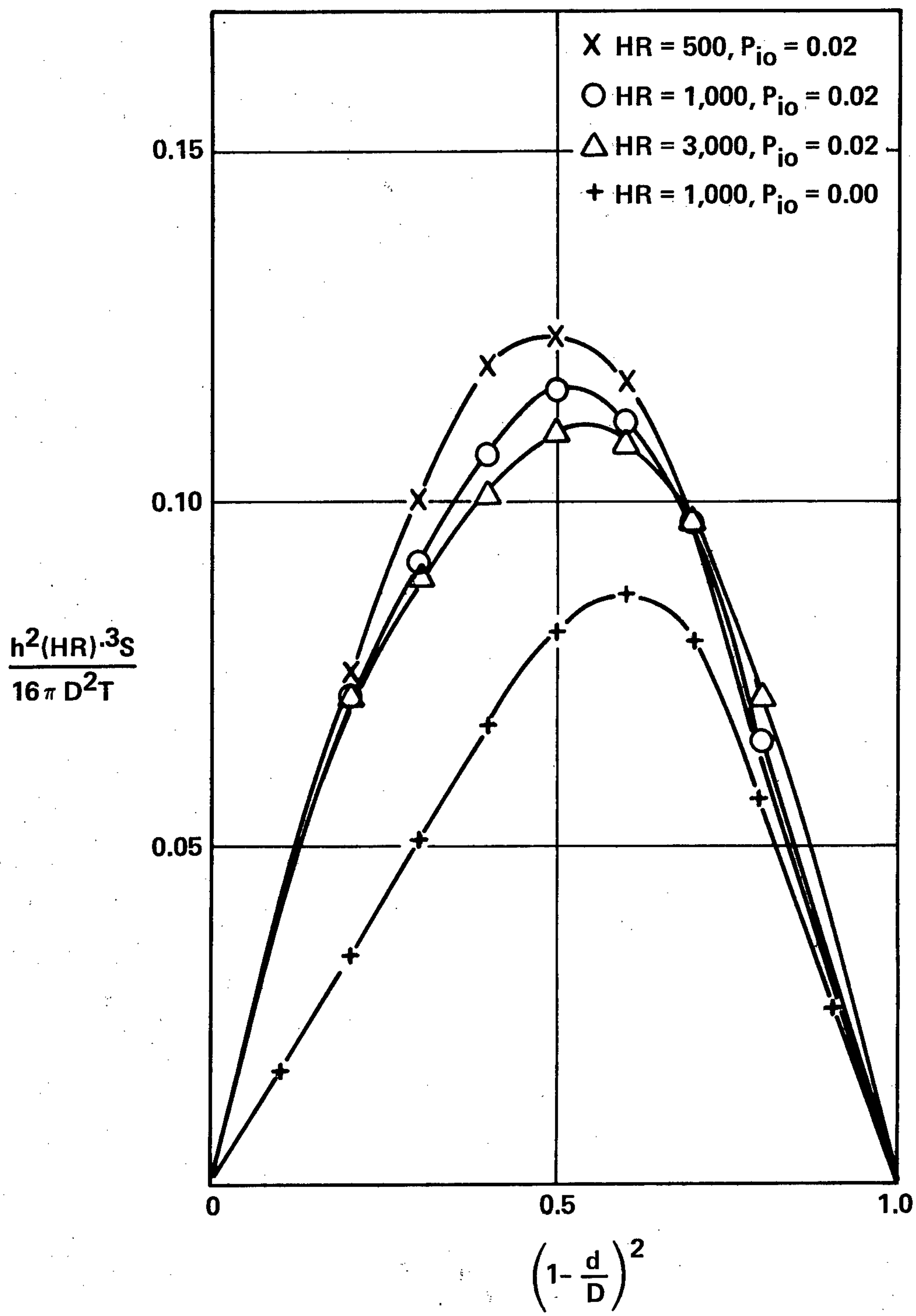

Figure 8. Lift Loss $h^2(HR)^{.3}S/16\pi D^2T$ versus $(1-d/D)^2$

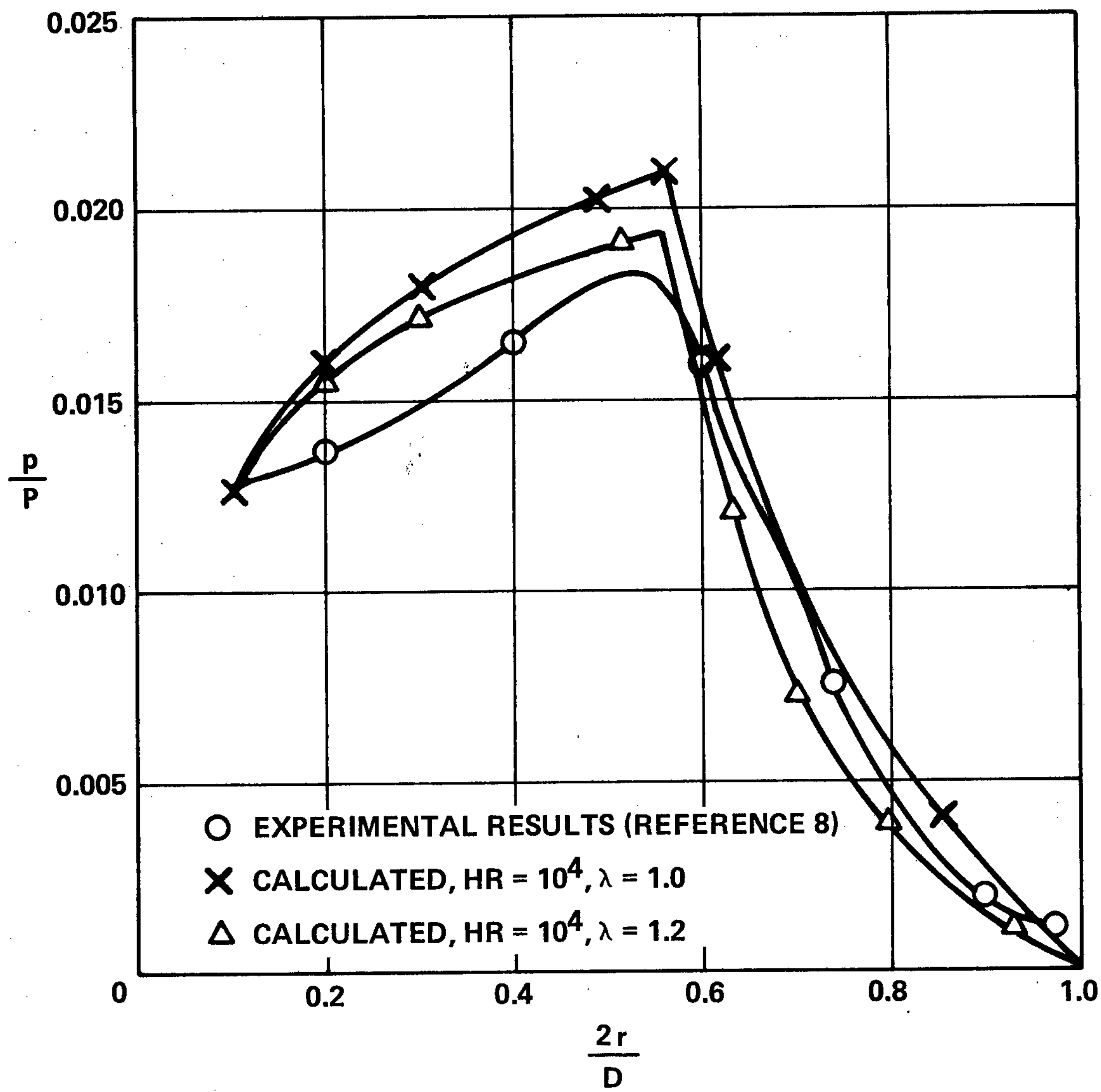

Figure 9. Surface Pressure Distributions, P_{io} = 0.01267

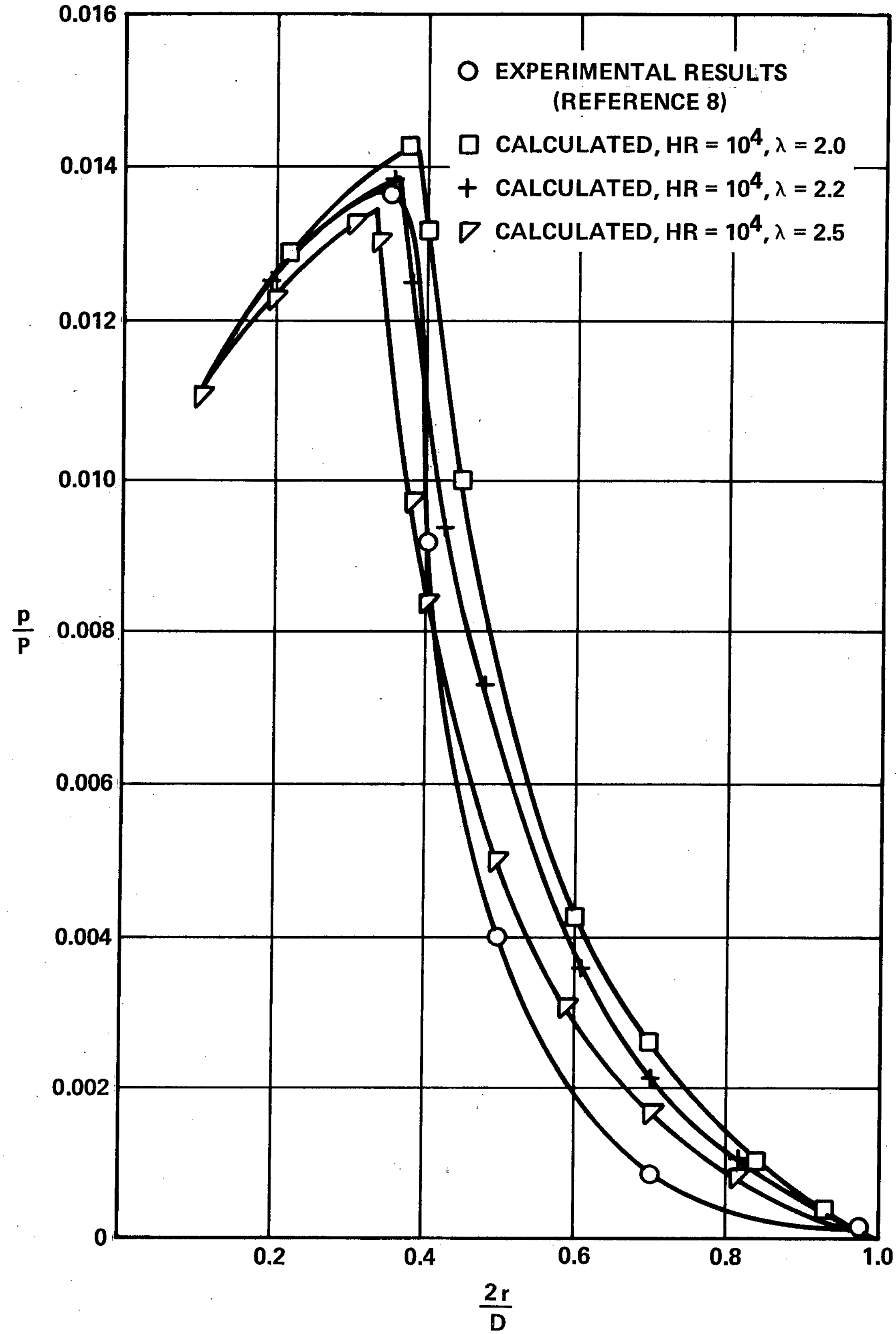

Figure 10. Surface Pressure Distributions, p_{io} = 0.01108

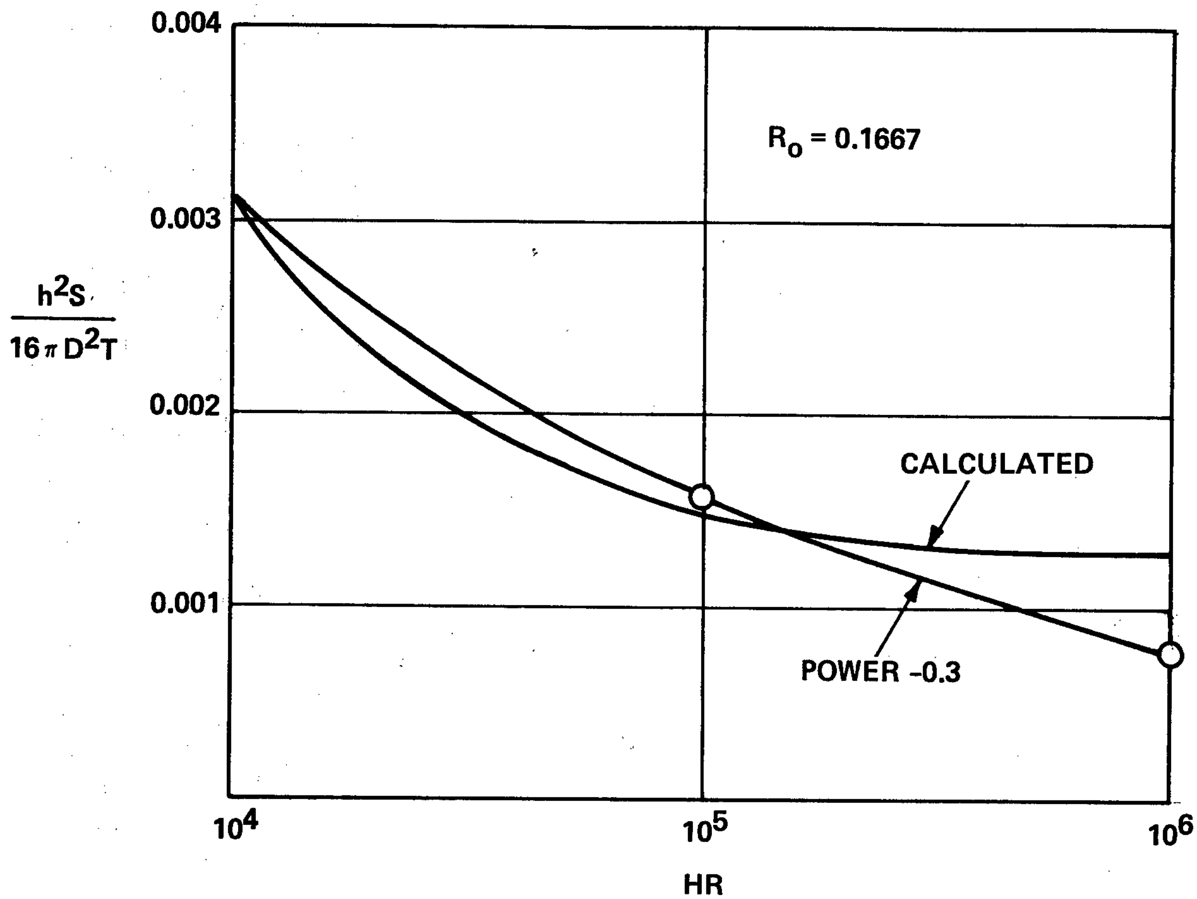

Figure 11. Dependence of $h^2S/16\pi D^2T$ on HR - High HR

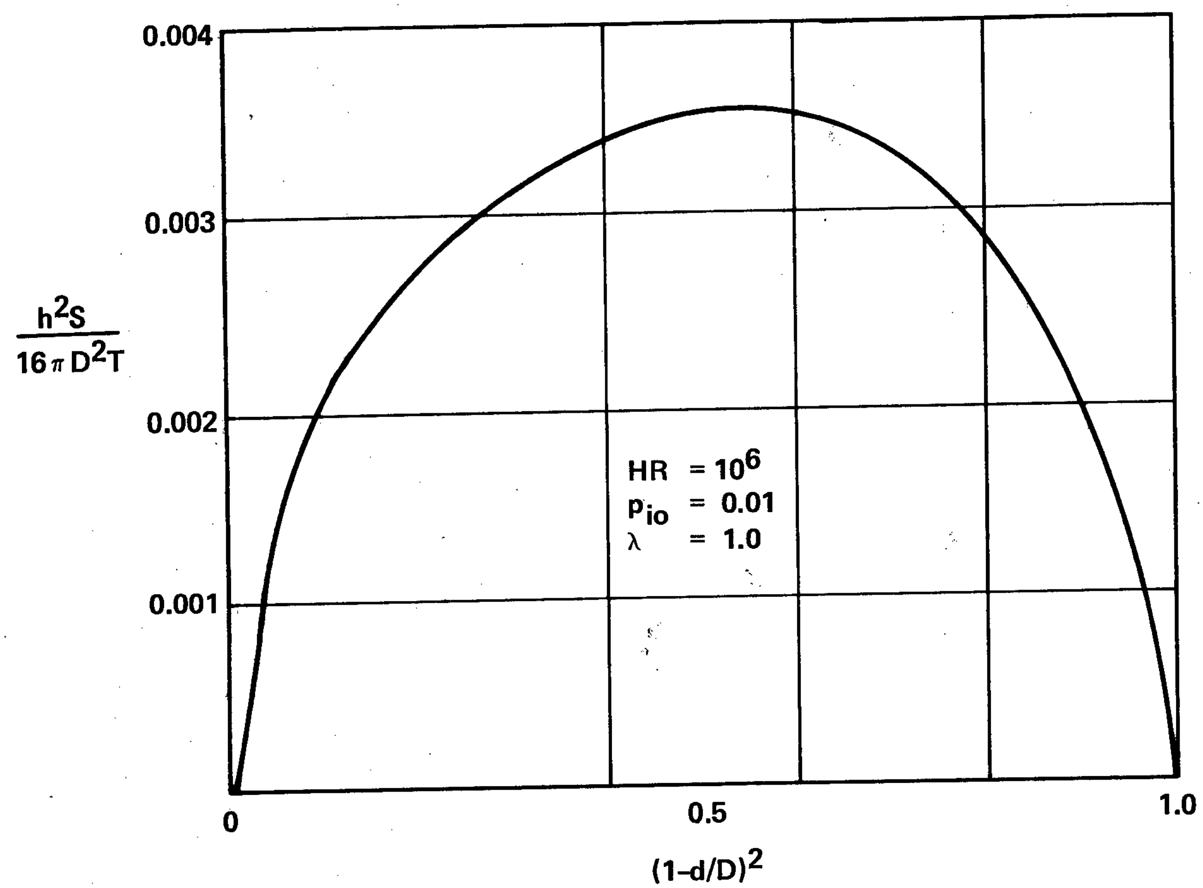

Figure 12. Lift Loss $h^2S/16\pi D^2T$ for $HR = 10^6$, $p_{io} = 0.01$ and $\lambda = 1.0$

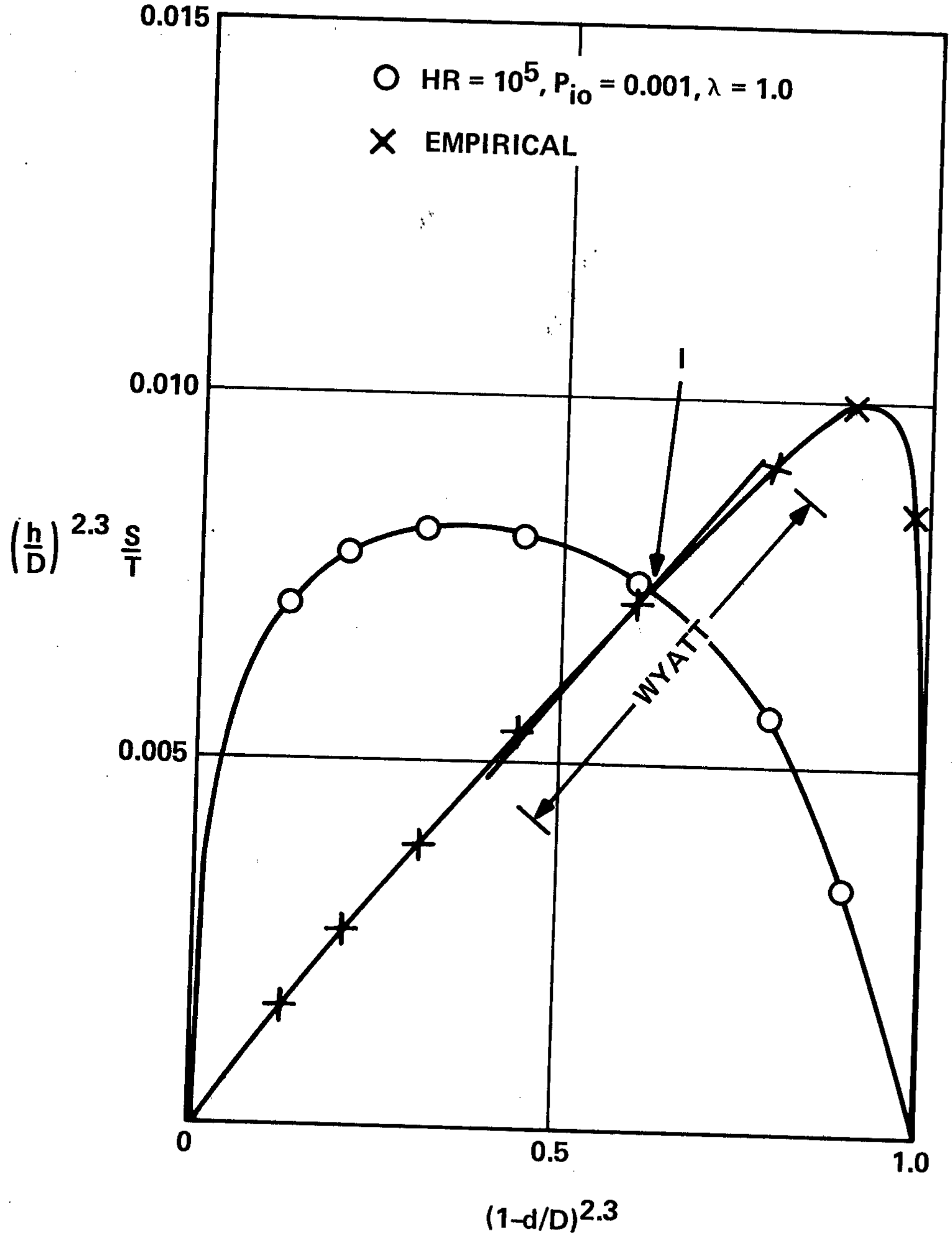

Figure 13. Lift Loss $(h/D)^{2.3}$ S/T versus $(1-d/D)^{2.3}$

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